Simulating Haptic Feedback Using Vision: a Survey of Research and Applications of "Pseudo-Haptic Feedback"

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ABSTRACT

This paper presents a survey of the main results obtained in the field of "pseudo-haptic feedback": a technique meant to simulate haptic sensations in virtual environments using visual feedback and properties of human visuo-haptic perception. Pseudo-haptic feedback uses vision to distort haptic perception and verges on haptic illusions. Pseudo-haptic feedback has been used to simulate various haptic properties such as the stiffness of a virtual spring, the texture of an image, or the mass of a virtual object. This paper describes the several experiments in which these haptic properties were simulated. It assesses the definition and the properties of pseudo-haptic feedback. It also describes several virtual reality applications in which pseudo-haptic feedback has been successfully implemented, such as a virtual environment for vocational training of milling machine operations, or a medical simulator for training in regional anesthesia procedures.

1. INTRODUCTION

Pseudo-haptic feedback is a technique for simulating haptic sensations in a novel way, capitalizing on the properties of human perception. Pseudo-haptic feedback uses visual feedback and verges on sensory illusion.

For example, let us assume that a user manipulates an object in a virtual environment and makes it move through a narrow passage. The objective is to simulate the haptic sensation of friction that occurs as the user inserts the object into the virtual passage. We assume that the user moves the virtual object using an isometric input device such as the Spaceball[1]. The motion of the virtual object is controlled by the force exerted by the user on the Spaceball. Let us assume that when the virtual object enters the narrow passage the velocity of the visual object is artificially reduced. In response to this visual deceleration, the user can increase the force exerted on the interface to make the object move through the passage. The combination of the manipulated object's deceleration and the increase in force exerted on the interface to make the object move through the passage gives the user an impression of resistance and friction, despite the fact he/she is not using a haptic interface. This type of perceived effect, which in this example creates the impression of friction, has been named *"Pseudo-haptic feedback"* (Lécuyer, Coquillart, Kheddar, Richard, & Coiffet, 2000). In a way, the user generates and controls the force feedback himself/herself by increasing or decreasing the pressure on the static device.

Pseudo-haptic feedback has been the focus of many experiments that have simulated various haptic properties such as friction, stiffness, or texture of virtual objects. In this paper, we will begin by

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[1] A Spaceball is an *isometric* input interface. Zhai (Zhai, 1995) classified the input devices into two categories: *isometric* devices which are static, offer resistance and stay put while you exert force on them; and *isotonic* devices which offer no significant resistance and are used to track users as they move around. A Spaceball features force sensors that measure compression or torsion efforts applied to it. These forces can then be used to move 3D objects in virtual reality simulations. Today, these interfaces are widely used in the world of CAD: Computer Aided Design.

introducing related work in the field of visuo-haptic integration and haptic illusions. Then we will give the founding ideas of the concept of pseudo-haptic feedback. We will then review the several haptic properties that have been simulated to date using pseudo-haptic feedback. Next, we will assess the potential applications of pseudo-haptic feedback in virtual reality. Finally, we will draw lessons from past experiences in implementing and evaluating pseudo-haptic systems.

2. VISUO-HAPTIC INTEGRATION AND HAPTIC ILLUSIONS

The endeavor to understand the mechanisms behind visuo-haptic integration has formed the subject of on-going debates for over a century and are still very much unresolved. To date, several models for multimodal perception and visuo-haptic integration have been put forward (Cornilleau-Pérès & Droulez, 1993) (Ernst & Banks, 2002) (Ghahramani, Wolpert, & Jordan, 1997) (Guest & Spence, 2003). As an example, Ernst and Banks proposed a statistical model for visuo-haptic integration, which was backed up by psychophysical experiments (Ernst & Banks, 2002). This model stipulates that the weight attributed to visual and haptic information is related to the independent performance of each of the two sensory channels (unimodal performance). The experiment conducted by Ernst and Banks to validate their model involved estimating a spatial parameter: the length of a side of a cube. By reducing the sharpness of the cube's visual contour (i.e. by adding noise to the cube's visual feedback), they observed that the weight attributed to vision by the perceptive system was reduced in proportion to the degradation in visual performance. In this way, the researchers demonstrated that the greater the efficiency of a sense in measuring a property, the more the perceptive system will make use of that sense when perceiving that property.

To study the weight attributed to visual and haptic information by human perception, researchers tend to use tasks that create sensory conflicts. A sensory conflict implies that the haptic information simulated in

the experiment differs slightly from the visual information (Hatwell, Streri, & Gentaz, 2003). By forcing

the subject to respond, we can estimate the weight attributed to the two sensory modalities by human

perception when evaluating the given property. In 1964, Rock and Victor came up with a pioneering

sensory conflict approach to investigate the phenomenon (Rock & Victor, 1964). In their experiment,

they asked subjects to touch a cube while viewing it through a lens that distorted its shape. When asked

to describe the cube's shape, the participant systematically chose a rectangular shape that corresponded

exactly to the visual shape. This demonstrated not only visual "dominance", but also complete "visual

capture": the response and estimation were entirely based on vision. Since this pilot experiment, many

studies have contrasted the phenomenon of visual dominance. These studies demonstrate, most notably,

that when spatial interaction tasks are concerned, visuo-haptic coupling is indeed characterized by strong

visual dominance (Hatwell et al., 2003). However, when perceiving textures and material properties,

weighting and sensory compromise tend to favor the sense of touch (Hatwell et al., 2003).

Additionally, Ernst and Bank's model (Ernst & Banks, 2002) may explain the behavioral results

observed during sensory conflict tasks referenced in the bibliography. According to this model, when the

sensory conflict concerns a spatial property, the Central Nervous System (CNS) will select the visual

modality, as the visual sense processes this property with greater precision than the haptic sense.

However, when the sensory conflict concerns textures, the CNS will select the haptic modality, as it

offers greater precision (greater unimodal performance) than the visual modality when estimating

material properties (Hatwell et al., 2003).

According to some researchers, the concept of sensory coherence is dominant when perceiving and

representing the environment. Cornilleau-Pérès and Droulez have come up with a multisensory fusion

model for 3D sensorimotor interaction that approaches the issue in terms of sensory coherence

(Cornilleau-Pérès & Droulez, 1993). They theorized that sensory signals are not processed by the CNS as a series of measurements, but rather as a series of constraints on mental estimations. Thus, sensory signals are not used to directly estimate the relevant variables, but rather to estimate the difference between mental estimations and the relevant variables. Under these conditions, Berthoz suggested that sensory illusion should not be considered as an error or wrong solution, but rather as the *"best possible hypothesis"* (Berthoz, 1998).

Illusions are generally considered to be errors of the senses. However, in reality, they are errors committed by the brain rather than by the senses (Goldstein, 1999). The brain is mistaken when interpreting the signals transmitted by the sensory channels which themselves are actually faithful to the reality of the stimulation. Optical illusions have been studied by scientists for many years (Nino, 1998). Sensory illusions involving the sense of touch, known as haptic illusions, also exist and can be demonstrated by simple experiments (Ellis & Lederman, 1993). For instance, Thaler's haptic illusion can be reproduced very easily. Simply place a coin in a refrigerator for a few minutes. When taken out, this coin appears to be heavier than an identical coin kept at room temperature. The haptic illusion described by Day is based on the principle of Bourdon's optical illusion: a subject will see a slight inflexion in the upper surface of an object which is actually perfectly straight (Day, 1990). On average, subjects of Day's experiment would haptically perceive an angle of deviation of 3.8 degrees, whereas Bourdon's optical illusion produces the visual perception of an angle of 3.5 degrees.

The fact that the same sensory illusion applies to both vision and touch raises questions about the nature of cognitive processes related to illusions. In fact, as Hatwell et al. point out, the presence of an illusion applying to both vision and touch suggests that the illusion is the result of similar processes affecting both modalities, and that such illusions are based on the same rules and representations of properties of

the real world (Hatwell et al., 2003). However, Hatwell et al. also note that certain illusions apply exclusively to one particular sense. These illusions are therefore the result of the specific nature of certain processes acting on that one sensory modality. However, various questions pertaining to the nature, generation and underlying properties of sensory illusions remain unanswered.

Vision can also be used to confuse haptic perception and generate haptic illusions. Srinivasan et al. found that vision could mislead a subject during a compliance discrimination task between two springs (Srinivasan, Beauregard, & Brock, 1996). The displacement of the springs was visually observed on a computer screen, while springs were compressed manually by means of a mechanical apparatus. The researchers observed that a contradictory visual feedback of the spring's displacement could alter the haptic perception of stiffness, and thus the result of the discrimination task. Biocca et al. reviewed visual-to-haptic intersensory biases and cross-modal interactions (Biocca, Kim, & Choi, 2001). They proposed an experiment to explore vision-touch synesthesia[2] in a virtual environment. In their experiment, participants manipulated the visual analog of a physical force and reported haptic sensations of physical resistance, even though the VR setup did not include a haptic display. They showed that this cross-modal illusion was correlated with and dependent upon the sensation of spatial and sensory presence. Thus, they concluded that presence may derive from the process of multimodal integration and, therefore, may be associated with other illusions, such as cross-modal transfers, that result from the process of creating a coherent mental model of the space. They also suggested that "these perceptual phenomena could be used to improve user experiences with multimodal interfaces by supporting limited

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[2] Biocca et al. defined *synesthesia* in their VR set-up as "*a perceptual illusion in which stimulation to a sensory modality connected to the interface (such as the visual modality) is accompanied by perceived stimulation to an unconnected sensory modality that receives no apparent stimulation from the virtual environment (such as the haptic modality)*" (Biocca et al., 2001).

sensory displays (such as haptic displays) with appropriate synesthetic stimulation to other sensory modalities".

3.   CONCEPT OF PSEUDO-HAPTIC FEEDBACK

The objective of pseudo-haptic feedback is to simulate haptic sensations, such as stiffness or friction, without necessarily using a haptic interface. This also means dispensing with passive manipulation devices like tangible devices or "props[3]" (Hinckley, Pausch, Goble, & Kassell, 1994) and abstaining from "sensory substitution" (Bach-y-Rita, Webster, Thompkins, & Crabb, 1987), which transposes haptic information in a very radical way. Therefore, pseudo-haptic feedback aims at providing a simulation of haptic sensations without using traditional techniques. The method used to achieve this falls within the realm of human perception and borders on sensory illusion. To simulate haptic sensations, pseudo-haptic feedback relies on visual feedback[4]. Pseudo-haptic feedback combines visual feedback in a synchronized way with the user's motion or sensory-motor action during simulation. In light of current understanding in the field of pseudo-haptic feedback based on visual feedback, we can formulate the following concept for pseudo-haptic feedback: pseudo-haptic feedback corresponds to the perception of a haptic property that differs from the physical environment, by combining visual and haptic information and proposing a new coherent representation of the environment.

The principle of pseudo-haptic feedback consists of combining visual feedback with the subject's actions in the virtual environment in novel way. The user is stimulated by an incoherent set of real-time visual

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[3] Hinckley et al. have proposed the notion of "*passive interface prop*" for the design of 3D user-interfaces (Hinckley et al., 1994). This represents a "*physical manipulation of familiar real-world objects in the user's real environment*".

[4] In the remainder of this paper we will concentrate on the "visual to haptic" case as no paper has yet been published on pseudo-haptic feedback involving senses other than vision, such as the auditory sense.

and haptic stimuli. Pseudo-haptic feedback should enable the subject to regain a sense of coherence in his or her interaction with the virtual world. Pseudo-haptic feedback should correspond to the subject's reinterpretation of these stimuli and to the optimal visuo-haptic perception of a world which must remain (or must become) coherent for the subject.

We can therefore state the following four key assertions concerning pseudo-haptic feedback. First, pseudo-haptic feedback implies one or more sensory conflicts between visual and haptic information. Second, pseudo-haptic feedback probably relies on the sensory dominance of vision over touch when perceiving spatial properties (distance, position, size, displacement amplitude, etc.). Third, pseudo-haptic feedback may correspond to a new and coherent representation of the environment resulting from a combination of haptic and visual information. Fourth, pseudo-haptic feedback may create haptic illusions, i.e., here, the perception of a haptic property different from the one present in the real environment.

To illustrate this concept, the following section focuses on a detailed list of successful examples of pseudo-haptic effects.

4. SIMULATING HAPTIC PROPERTIES WITH PSEUDO-HAPTIC FEEDBACK

To illustrate the potential of pseudo-haptic feedback, we will describe, in turn, the different haptic properties that have been simulated to date using pseudo-haptic feedback.

4.1 PSEUDO-HAPTIC SIMULATION OF FRICTION

The first example of pseudo-haptic feedback was developed to simulate friction (Lécuyer, Coquillart, Kheddar, Richard, & Coiffet, 2000). This possibility was qualitatively assessed during a pilot experiment conducted on 18 subjects. The subjects were asked to move a cube horizontally across a simple virtual

environment and, more specifically, to slide the cube across a grey area to the right of the screen (see Figure 1). They used either a Spaceball 2003C or a standard 2D mouse (and not a haptic interface) to move the cube. As the cube moved over the grey area, it could either be slowed down or accelerated. The simulation therefore altered the gain in visual restitution, i.e. the ratio between the user's displacement of the input interface and the visual displacement of the object on the computer screen. This gain, which is a well-known parameter in the field of Computer-Human Interaction (CHI), is known as the *C/D ratio* (or "Control/Display ratio" (Lécuyer, Burkhardt, & Etienne, 2004) (Dominjon, Lécuyer, Burkhardt, Richard, & Richir, 2005)). The subjects were asked to describe the sensation they had felt when moving the cube across the grey area by selecting a description from a given list.

Figure [1] here

Analysis of the subjects' choices according to variations in the C/D ratio used, show that "friction"-type expressions are systematically associated with an increased C/D ratio (slowing down of the cube as it passes over the grey area), whereas "sliding"-type expressions are systematically associated with a decreased C/D ratio (acceleration of the cube). Furthermore, if the C/D ratio is not altered while the cube moves over the grey area (constant visual velocity), the subjects select "nothing at all" from the list of available descriptions. It would therefore appear that changing visual gain (C/D ratio) when manipulating the cube effectively helps to suggest haptic-type phenomena, such as friction, using a passive input interface only (i.e. without using a haptic interface).

In another paper, Pusch et al. showed that a sensation of resistance to motion in a windy environment could also be achieved through pseudo-haptic feedback (Pusch, Martin, & Coquillart, 2008). This novel

sensation obtained in presence of virtual wind, and thus closer to viscosity, was obtained in presence of the visual feedback of the real user's hand. In their set-up, named "HEMP" (for Hand-Displacement-Based Pseudo-Haptics), the researchers could display the video of the user's real hand as obtained with real-time camera recording. The position of the hand's image was distorted and modified in the final visual display in order to generate the pseudo-haptic sensation. Experimental studies revealed that participants could actually feel the resistance of the wind with this technique implying a strong pseudo-haptic sensation (Pusch et al., 2008).

4.2 PSEUDO-HAPTIC SIMULATION OF STIFFNESS

Another property simulated using pseudo-haptic feedback is stiffness, i.e. the degree of hardness or softness of an object (Lécuyer et al., 2000b) (Lécuyer, Burkhardt, Coquillart, & Coiffet, 2001). To simulate the different degrees of stiffness of virtual objects using a Spaceball 2003C, researchers came up with the idea of combining the visual deformation of the object on which pressure is exerted (e.g. a virtual piston) with pressure exerted on the Spaceball (see Figure 2). When a given pressure is exerted on the Spaceball, the object represented on the computer screen is deformed to a greater or lesser degree. The resulting hypothesis is that the greater the visual deformation of the object (the piston's displacement), the more this object will appear to be soft. Conversely, if there is only a slight visual deformation, the object will appear to be hard.

Figure [2] here

In accordance with Hooke's law (Equation 1), the internal and constant stiffness of the Spaceball ($K_{spaceball}$) is related to the force (F_{user}) that the user exerts on the interface and also to the displacement

(D_{user}) of the user's thumb at the extremity of the interface. The researchers assume that the stiffness perceived by the user ($K_{virtual}$) may correspond instead to the relationship between the force exerted by the user and the visual displacement of the virtual piston ($D_{virtual}$) observed on the screen. The researchers therefore assume that, in the user's mental model of stiffness (see Equation 2), visual displacement will strongly dominate the user's physical displacement. By altering the piston's displacement on the screen, it would become possible to perceive an extremely wide range of virtual stiffness.

$$F_{user} = K_{spaceball} * D_{user} \qquad (1)$$

$$K_{virtual} = F_{user} / D_{virtual} \qquad (2)$$

This hypothesis was quantitatively supported by a psychophysical experiment conducted on 20 subjects (Lécuyer et al., 2000b). The experiment involved discriminating between different degrees of stiffness (selecting the stiffest spring) and was conducted using a real spring and a virtual spring simulated by the pseudo-haptic device described above. The results of this experiment demonstrate that when the virtual stiffness, simulated by the pseudo-haptic device, is compared with the stiffness of a real spring, the performance is similar to discriminating between two real springs. This suggests that, from a perceptual point of view, pseudo-haptic virtual stiffness is similar to that of a real spring.

Figure [3] here

A type of sensory illusion phenomenon was observed at the end of this experiment when a test was conducted on the last 10 subjects (Lécuyer et al., 2000a). These subjects were asked to draw a line

corresponding to the maximum displacement of their thumb when they pressed the Spaceball. Given that the Spaceball could only move 5mm before reaching the mechanical stop, an obvious overestimation of this distance was observed (see Figure 3). This overestimation corresponds roughly to the maximum displacement of the virtual pistons on the computer screen. This result therefore suggests that the subjects' proprioceptive perception of their thumb displacement was "blurred" by visual displacement. The experiment suggests an illusion of the proprioceptive sense which in this case is "blurred" by vision.

This proprioceptive illusion could be partially explained by Ernst and Banks' model (Ernst & Banks, 2002) as the pseudo-haptic setup generates here a sensory conflict concerning the displacement of the piston. According to this model, the visual information of displacement is expected to dominate the haptic one, which is probably less reliable in the human perceptual process. In addition, in the experimental set-up used here, visual and haptic sources of information were not co-located. It was found in (Congedo, Lécuyer, & Gentaz, 2006) that spatial "de-location" promotes visual dominance instead of visuo-haptic integration, and that the "de-location of perceptual information appears to increase considerably the weight of the dominant sense at the expenses of the other". This might explain the near-substitution of haptic displacement by the visual one.

As the Spaceball is a static passive interface, its reaction force is, at any one time, equal to the pressure exerted on it by the user. Thus, a unique property of pseudo-haptic feedback when using an isometric interface is that the force fed back to the user is always equal to the user's input: it is the user (rather than the computer) that controls the force feedback in relation to the visual stimuli. Therefore, the user of such a pseudo-haptic system creates his/her own force feedback constantly. Here, pseudo-haptic feedback represents the transfer of the control of force feedback from the computer to the subject, as the subject tries to make the world that he/she perceives as coherent as possible.

Paljic et al. replicated these results in a similar experiment applied to the perception of torsion stiffness (Paljic, Burkhardt, & Coquillart, 2004). They showed that the subjects of their experiment were also able to compare real torsion springs with virtual torsion springs simulated using pseudo-haptic feedback. The virtual torsion springs were simulated using two types of interface: either an isometric (and therefore static) input interface or an elastic input interface, i.e. a device that causes displacement. Interestingly enough, Paljic et al. found that the elastic device produced better results than the isometric one.

4.3 PSEUDO-HAPTIC SIMULATION OF MASS

Dominjon et al. studied the possibility of simulating the mass of objects manipulated in a 3D virtual environment using pseudo-haptic feedback (Dominjon et al., 2005). Once again, the researchers began by modifying the object's motion on the screen and therefore by artificially altering the C/D ratio. The researchers hypothesized that by speeding up the manipulated object, they could create the illusion that the object weighed less. Inversely, by slowing it down, they could create the impression that the object weighed more.

Figure [4] here

To confirm this hypothesis, the researchers conducted several psychophysical experiments focusing on the perception of the mass of virtual objects (balls), manipulated using a haptic interface (see Figure 4). These experiments showed that a C/D ratio of less than 1 (corresponding to visual amplification of the user's physical movements) significantly influenced the subjects' answers. Considerable visual amplification of the objects' motion could even cause the subjects to totally reverse their judgment and believe that a "physically" heavier object was lighter than another one.

This study has direct consequences on the use and design of haptic interfaces in virtual reality applications, as it demonstrates that the C/D ratio directly influences the haptic perception of the mass of objects in virtual environments. Thus, designers of virtual reality systems using haptic feedback must make sure that they fully control the C/D ratio in order to constantly control the haptic sensations produced.

4.4 PSEUDO-HAPTIC SIMULATION OF TEXTURE

Lécuyer et al. developed a technique for simulating texture and relief on 2D images displayed on the computer screen using pseudo-haptic feedback (Lécuyer et al., 2004a). When the user manipulates a computer mouse, the technique consists of altering the cursor's motion as it moves over the image. To create the impression that the cursor is climbing up a slope, it is slowed down. Inversely, to simulate the cursor sliding down a slope, it is speeded up. For example, to simulate the cursor moving over a bump (Figure 5), the cursor is slowed down until it reaches the top of the bump. Once it is past the top, the cursor accelerates, until it reaches the foot of the bump. After that, it returns to its normal speed.

Figure [5] here

This technique can be related to results obtained by Robles-De-La-Torre and Hayward concerning tactile perception of relief and macroscopic textures (Robles-De-La-Torre & Hayward, 2001). These researchers demonstrated that lateral force dominates the perception of vertical motion as the finger passes over texture. The proposed pseudo-haptic technique transposes lateral forces to the visual feedback, by accelerating and decelerating the cursor. Some "virtual" lateral forces are directly applied to the cursor, rather than to the subject's finger.

The proposed technique was evaluated during three experiments (Lécuyer et al., 2004a). The first experiment measured the capacity to identify simple bumps or holes (see Figure 6). The second experiment studied the capacity to recognize relief relying solely on information about cursor movement (without any other visual information, i.e. without the white cache displayed on Figure 6). The third experiment studied relief perception in more details by asking subjects to draw the profile of the surfaces covered. Finally, these three experiments demonstrated that the subjects were able to recognize and precisely draw textures and relief simulated using pseudo-haptic feedback.

Figure [6] here

In a second paper, Lécuyer et al. proposed another pseudo-haptic technique to enhance the previous technique and simulate texture sensations by varying the size of the cursor according to the texture displayed on the computer screen (Lécuyer, Burkhardt, & Tan, 2008). With this so-called "Size technique", the user sees an increase (or decrease) in cursor size corresponding to a positive (or negative) slope in the texture. Interestingly, it was found that the two techniques reinforce each other: when they were consistently combined, the participants were more efficient in identifying the shapes of simulated bumps and holes. A slight dominance of the Size technique was also observed in conflict situations. Taken together, these results promote the use of both techniques for the low-cost simulation of texture sensations in applications such as videogames or graphical user interfaces, which are described in the following section.

5. CURRENT APPLICATIONS OF PSEUDO-HAPTIC FEEDBACK

5.1 VIDEO GAMES

Various video games use effects that could be considered to be pseudo-haptic. For example, driving simulators often add special effects when the vehicle drives over slippery areas or areas that slow it down (oil puddle, grass, sand, etc.). The user continues to manipulate the input interface (joystick, game pad or mouse) in the same way, yet the vehicle in the virtual environment becomes more difficult to move or control. This type of effect may enable the user to "feel" the characteristics of the ground that he/she is driving over or give the impression that the vehicle that he/she is driving is "heavy". The sensations created and methods used in this case are very similar to those used by pseudo-haptic feedback. Video games have therefore been using the pseudo-haptic feedback technique for a long time (perhaps without realizing it) to simulate the physical state of an object or character being controlled in the simulation: friction beneath the wheels of a car, inertia of a skier, weight of a wrestling opponent, tiredness of an avatar, etc.

5.2 TACTILE IMAGES

The technique of pseudo-haptic textures can be used to simulate the relief of 2D images with standard input devices (computer mouse). A generic algorithm which uses a topography or height map of the image has been patented (Lécuyer, Etienne, & Arnaldi, 2004). The height map can, for instance, be computed from the different grayscale levels of the pixels in the image, as in several haptic texturing algorithms (Basdogan, Cho, & Srinivasan, 1997). Then, the algorithm operates on the theoretical trajectory of the cursor pixel by pixel. It alters the cursor's motion according to the heights that it encounters. For instance, when the cursor moves from a low pixel (a dark pixel, for example) to a high

pixel (a light pixel), it decelerates. The final visual position reached by the cursor takes all the accumulated accelerated and decelerated motions into account. This algorithm can be quickly installed in various applications, such as image editing or web browsing, to add new effects to the cursor, such as the capacity to perceive relief or contours of pictures or web pages. This technique could also be used to immerse video gamers deeper into the game by giving them new tactile sensations.

An entertaining application of this technique concerns the perception of images displayed on the computer screen. This involves making more information appear for a wide audience when interacting with computers and, in particular, restoring the third dimension to 2D images. Various demonstrations of "*Tactile Images*" can be found on the internet (http1) in which users can enjoy feeling the contours and relief of various photos and images.

5.3 GRAPHICAL USER INTERFACES

Studies by Rodgers (Rodgers, 2005) and Mandryk et al. (Mandryk, Rodgers, & Inkpen, 2005) focus on the application of pseudo-haptic feedback in the field of Graphical User Interfaces (GUI). They have developed a set of "pseudo-haptic widgets" which are standard widgets such as icons or sliders augmented with pseudo-haptic effects. With such effects, the widgets displayed on the computer screen can become sticky, magnetic, repulsive, etc. Pseudo-haptic widgets were evaluated by Mandryk et al. in the context of multi-monitor displays, when accessing widgets and tools located on the borders of the displays (Mandryk et al., 2005). Sticky boundary widgets were designed to reduce the number of accidental transfers to the other display. Researchers compared pseudo-haptic widgets ("sticky" scrollbars) to a standard widget (standard scrollbar) for several multi-monitor display configurations. They concluded that "pseudo-haptic technique can be used to create sticky widgets at the edge of a monitor" (Mandryk et al., 2005). The pseudo-haptic feedback was found to improve users' performance

by significantly reducing errors for accessing a boundary widget, reducing the number of accidental crossovers to the wrong display, and decreasing selection time.

5.4 DATA MINING

An application of pseudo-haptic textures was proposed by Schoor et al. in the field of manual data mining for the segmentation of digitized microtome tissue slices of barley grains (Schoor et al., 2008). They introduced a pseudo-haptic technique combined with an automatic zooming technique for improved navigation in large amounts of biological image data. The automatic zooming depends on mouse speed and enables users to navigate with a tighter focus during segmentation. The pseudo-haptic technique is based on image data and is meant to compensate for user's inaccuracies generated by shaky hands. The researchers found that the combination of both techniques improved overall performance of segmentation in terms of both accuracy and task completion time. Some users even described their impression of pseudo-haptics as a "magical force" that binds the cursor to the correct position in an image or leads it there (Schoor et al., 2008).

5.5 VIRTUAL TECHNICAL TRAINER

The Virtual Technical Trainer (VTT) (Crison et al., 2004) (Crison et al., 2005) is a virtual environment designed for vocational training programs run by AFPA (French National Association for Vocational Training of Adults). AFPA trainees sign up for a year-long course in how to use milling machines. The VTT system provides a virtual reality simulation of the milling process (see Figure 7a). VTT offers direct and interactive manipulation of a virtual cutting tool (milling machine). When the manipulated cutting tool machines cuts a piece of metal, the trainee can "feel" the cutting action, which varies according to different simulation parameters (type of material, rotation speed of the milling tool, etc.).

The VTT designers' theory is that the direct perception of the cutting action accelerates understanding of the machining process and the relationship between the different mechanical parameters involved.

Figure [7] here

In the simulator's latest version, the cutting process can be simulated in different ways. Firstly, a haptic interface can be used, either a PHANToM generic device (Crison et al., 2004) or a device which is "custom made" for the application (Crison et al., 2005). Secondly, pseudo-haptic feedback can be used (Crison et al., 2004). In this case, the VTT system uses passive input interfaces, such as the SpaceMouse elastic interface (see Figure 7b). When the virtual piece of metal is being machined, the visual displacement of the tool is decelerated to a greater or lesser degree according to the simulation parameters (rotation speed, depth of drill, type of tool, etc.), in compliance with the principle described in section 4.1 which concerns the simulation of friction. The different cutting efforts are therefore simulated simply using pseudo-haptic feedback as the SpaceMouse is moved.

The first perceptive tests conducted using pseudo-haptic feedback in the VTT system showed that variations in the cutting effort (resulting from the change in simulation parameters) was very well perceived by the trainees (Crison et al., 2004). Researchers will need to confirm the pseudo-haptic feedback approach as supporting the VTT system's educational objectives. They will also need to compare this approach with more typical haptic feedback in order to find the best compromise between the two.

MEDICAL SIMULATOR

Finally, pseudo-haptic feedback has been implemented and tested inside a medical simulator marketed to allow training in the procedures of loco-regional anesthesia (Bibin, Lécuyer, Delbos, Burkhardt, & Bonnet, 2008). This virtual reality simulator is designed to train anesthesiologists in the risky operation of nerve stimulation (see Figure 8).

Figure [8] here

The first step of the procedure calls for the anesthetist to palpate the patient's body, before inserting the needle and electrically stimulating the nerve. The palpation is necessary to locate the patient's organs under the skin, and to find a proper location to insert the needle. In order to simulate the palpation step, the designers of this medical simulator chose to use the technique of pseudo-haptic textures. Using a computer mouse, the anesthetist manipulates a spherical cursor which follows the surface of the skin of the patient, in order to palpate the subcutaneous organs. The pseudo-haptic texture technique is then applied to the visual motions of the cursor, to simulate the bumps and hollows corresponding to the positions of organs and arteries under the skin. With such a technique, the user can explore the patient's body in a more physical and realistic context.

6.   LESSONS LEARNED

In this section, we draw lessons from the different ways in which pseudo-haptic feedback is used in the various experiments and applications described above.

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6.1 SPECIFICITY OF PSEUDO-HAPTIC FEEDBACK

We can illustrate the specificity of pseudo-haptic feedback by defining what it is not, i.e. by showing how it differs from other types of haptic feedback:

• Firstly, pseudo-haptic feedback differs from "active" haptic feedback in that it does not necessarily require a haptic interface. A passive input device, such as a computer mouse or a joystick, may be adequate for pseudo-haptic feedback purposes.

• Secondly, pseudo-haptic feedback differs from using tangible devices or props in that props are fixed physical objects that have the same constant shape as the object being manipulated in the virtual environment (Hinckley et al., 1994). Pseudo-haptic feedback enables the manipulated object's properties to be dynamically modified (dynamic change of stiffness or mass, for example).

• Finally, pseudo-haptic feedback differs from sensory substitution since substitution transposes the haptic sensation by stimulating a different sense (visual or auditory sensation for example) (Bach-y-Rita et al., 1987), while pseudo-haptic feedback uses visual feedback and visuo-haptic interactions to simulate a sensation on the haptic channel.

Pseudo-haptic feedback therefore offers complementary possibilities in relation to the techniques currently known for simulating haptic information in a virtual reality system.

6.3 ILLUSION OR NOT?

The effect observed in Figure 3 might indicate the presence of sensory illusions in the pseudo-haptic process. The results of the experiments described in section 4.2 also show that it is possible to compare actual haptic sensations with sensations produced by pseudo-haptic systems (discrimination tests

between real and virtual stiffness (Lécuyer et al., 2000b) (Paljic et al., 2004)). The subjects of these experiments successfully formulated and characterized their perception of haptic properties that strongly differ from the physical environment. Therefore these phenomena have certain similarities to haptic illusions.

However, pseudo-haptic feedback could also be the result of a process related to the experiment itself and could correspond to the learning of a systematic association of sensorimotor displacement and visual feedback. Thus, the researchers are still undecided as to the nature and to the level of consciousness of the observed phenomenon (Lécuyer, 2001). Is it a sensory illusion (an inevitable process), or a strategic decision-making process (which is reversible)? In other words, is pseudo-haptic feedback really related to perceptual characteristics (haptic illusion)? Further research and experiments must be conducted before a definitive answer can be given to these questions.

6.4 INTER-INDIVIDUAL VARIABILITY

In the aforementioned set-ups, the researchers observed a high variability in results depending on the individual. During a stiffness discrimination task using pseudo-haptic feedback, Lécuyer et al. identified different types of reaction (Lécuyer et al., 2001). They decided to group the subjects into different categories according to their reactions. These groups corresponded to the potentially different influences of visual feedback on haptic perception. Although the majority of the subjects' answers were consistent, certain subjects (10% of the overall group) replied in a way that "tended toward the haptic" in that their answers did not appear to be influenced by visual feedback at all but solely by haptic feedback. Another so-called "marginal" group (also 10% of the overall group) gave surprising answers. For instance, in certain situations, even if a pseudo-haptic spring had greater visual and haptic stiffness than the actual

physical reference spring, these subjects nevertheless perceived the pseudo-haptic spring as being less stiff. As yet, no one has come up with an explanation for this intriguing behavior.

Therefore it would seem that individuals can react very differently to sensory conflicts and potential illusions produced by pseudo-haptic feedback. However, inter-individual variability is a typical element of psychology experiments. This suggests that additional work is required in terms of tuning and adapting pseudo-haptic systems.

6.5 USE OF INPUT DEVICES

Experiments conducted to assess pseudo-haptic feedback have shown that interfaces with very different features can be used to simulate pseudo-haptic feedback: isotonic devices (such as the computer mouse used to simulate texture (Lécuyer et al., 2004a)), isometric devices (such as the Spaceball used to simulate linear stiffness (Lécuyer et al., 2000b)), elastic interfaces (e.g. to simulate torsion stiffness (Paljic et al., 2004)) and even haptic devices (e.g. to simulate mass (Dominjon et al., 2005)).

When simulating friction, researchers have observed that subjects prefer to use isometric interfaces (Spaceball) rather than isotonic interfaces (2D mouse) (Lécuyer et al., 2000b). This preference is probably justified by the fact that the resistance (internal stiffness) of the isometric device produces true force feedback. Furthermore, Paljic et al. found their best results when using an elastic interface rather than a strictly isometric (and therefore static) one (Paljic et al., 2004). This would suggest that pseudo-haptic feedback is enhanced when using input interfaces that enable displacement and provide physical resistance, i.e., elastic interfaces.

6.6 USE OF C/D RATIO

All the experiments described above rely on a sensory conflict between the subject's actual physical movements and movements represented visually in the virtual environment. These experiments either modify the visual position of the object manipulated by the subject in the virtual environment (e.g. velocity of cursor for simulating texture (Lécuyer et al., 2004a)) or else they modify the visual dimensions of the manipulated object (deformation of a piston to simulate stiffness (Lécuyer et al., 2001)). Pseudo-haptic simulations are thus based on the control and variation of the C/D ratio, i.e. the relationship between the user's sensorimotor input and its visual result. In all pseudo-haptic simulations, the change in C/D ratio forces the user to resolve a visuo-haptic conflict centering on a spatial property. The state of the art in the field of visuo-haptic perception of sensory conflicts suggests that such conflicts are resolved in favor of vision and that visual displacement preferentially dominates actual physical sensorimotor displacement. This idea is confirmed by the proprioceptive "illusion" in Figure 3.

Researchers assume that this dominating visual spatial information is at the basis of the modified haptic perception of the manipulated object's properties. The idea put forward is that a visual spatial parameter (visual position, dimension, etc.) is introduced into the subjects' mental model of their haptic interaction with the manipulated object (Dominjon et al., 2005) depending strongly on the context of the application or experiment. To design a pseudo-haptic system that simulates a given haptic property, we could thus begin by identifying a law that controls this haptic property and associates it with spatial parameters (e.g. Hooke's law of Equation 1). Then we could set up a visuo-haptic sensory conflict focusing on a spatial parameter associated with this haptic property. Then, to modify the perception of the targeted haptic property and create pseudo-haptic feedback, we could simply modify the visual feedback of this spatial

parameter. Nevertheless, future work is also necessary to investigate the feasibility and efficiency of this method and the importance of the context of the application.

7.   CONCLUSION

Pseudo-haptic feedback is a simple way of simulating haptic sensations without using expensive haptic interfaces. Pseudo-haptic feedback corresponds to an ingenious use of the perceptive properties of visuo-haptic integration. Pseudo-haptic feedback relies on the combination of the user's sensorimotor actions in the simulation (for example, via a completely passive input interface) with the environment's visual feedback. Visual feedback is used as disrupting feedback, which generates effects similar to haptic illusions.

It has been demonstrated that pseudo-haptic feedback can be efficiently used to simulate sensations and multiple haptic properties, such as the stiffness of a virtual spring, the texture of an image or the mass of a virtual object. Today, pseudo-haptic feedback is implemented in different virtual reality applications, such as the VTT virtual environment for vocational training in operating milling machines, or a medical simulator for training in loco-regional anesthesia procedures.

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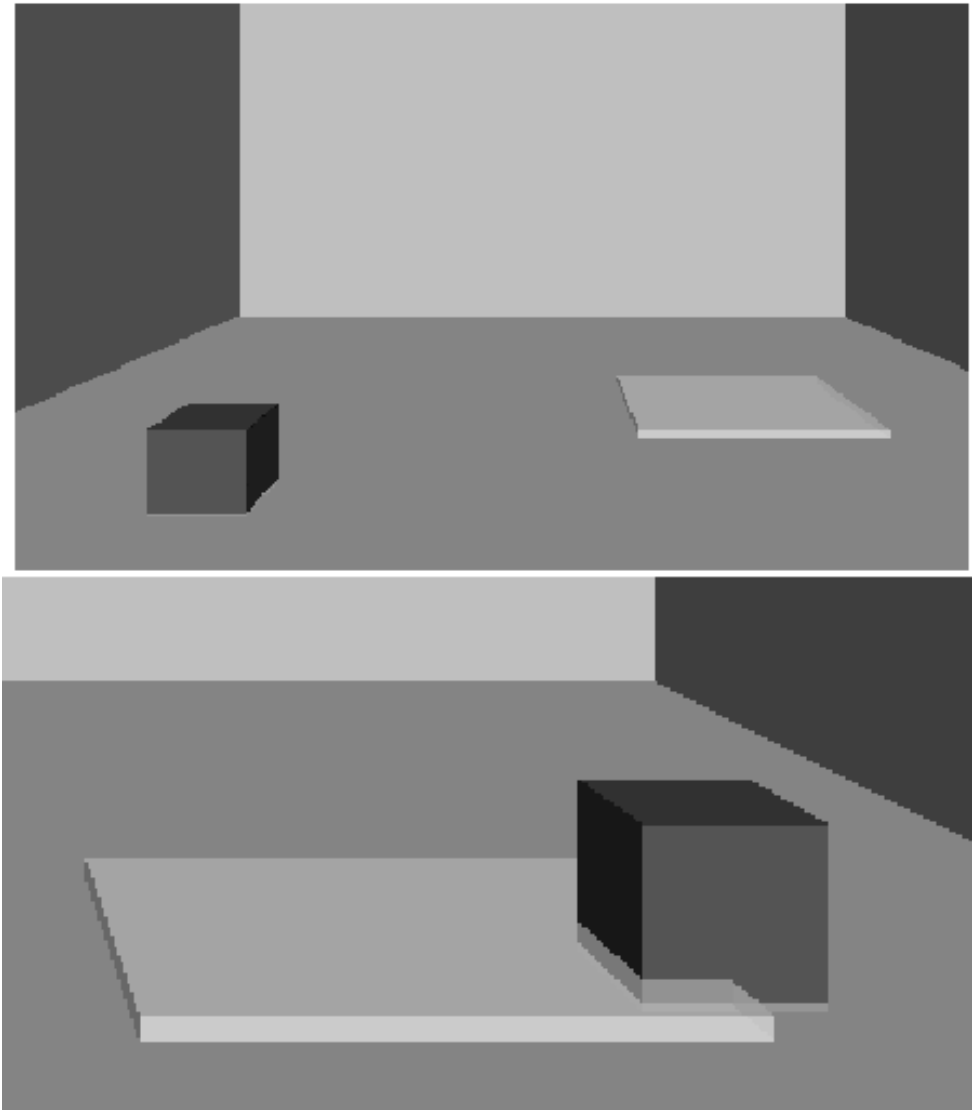
Figure 1: Pseudo-haptic simulation of friction: a cube moved by the user with a Spaceball crosses a grey area and is decelerated.
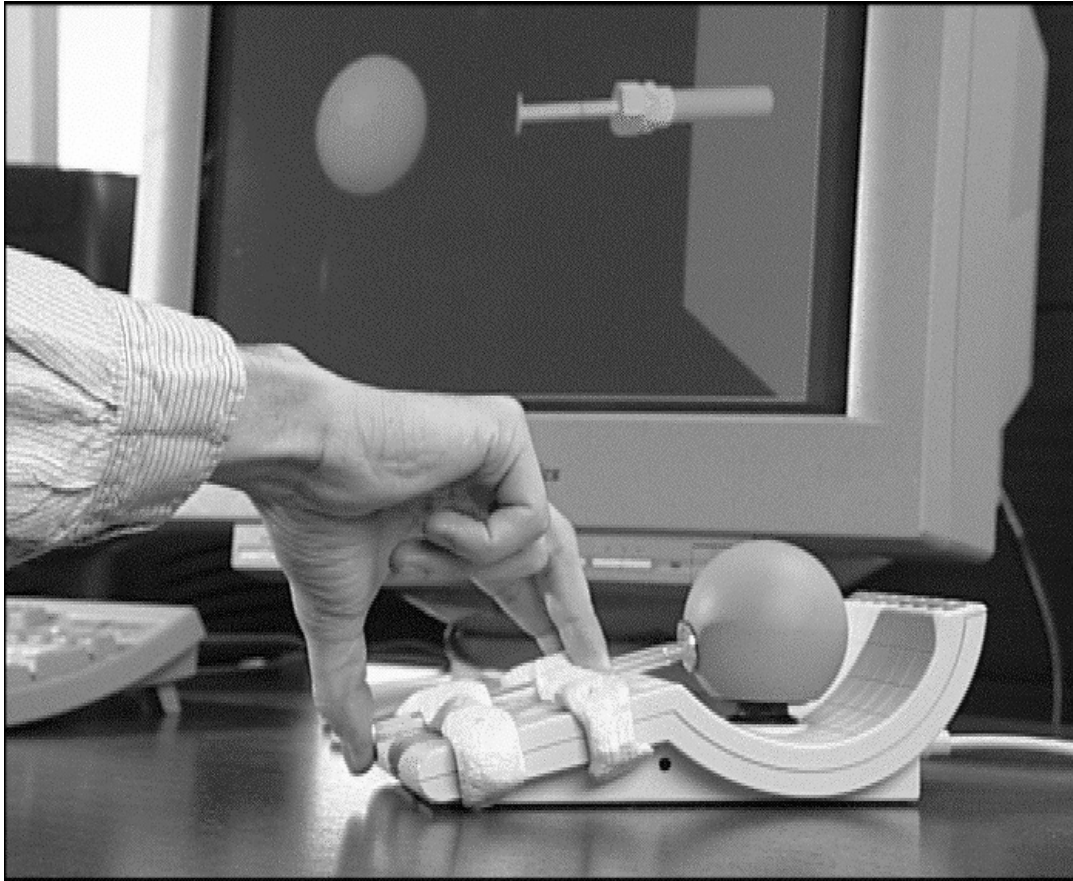
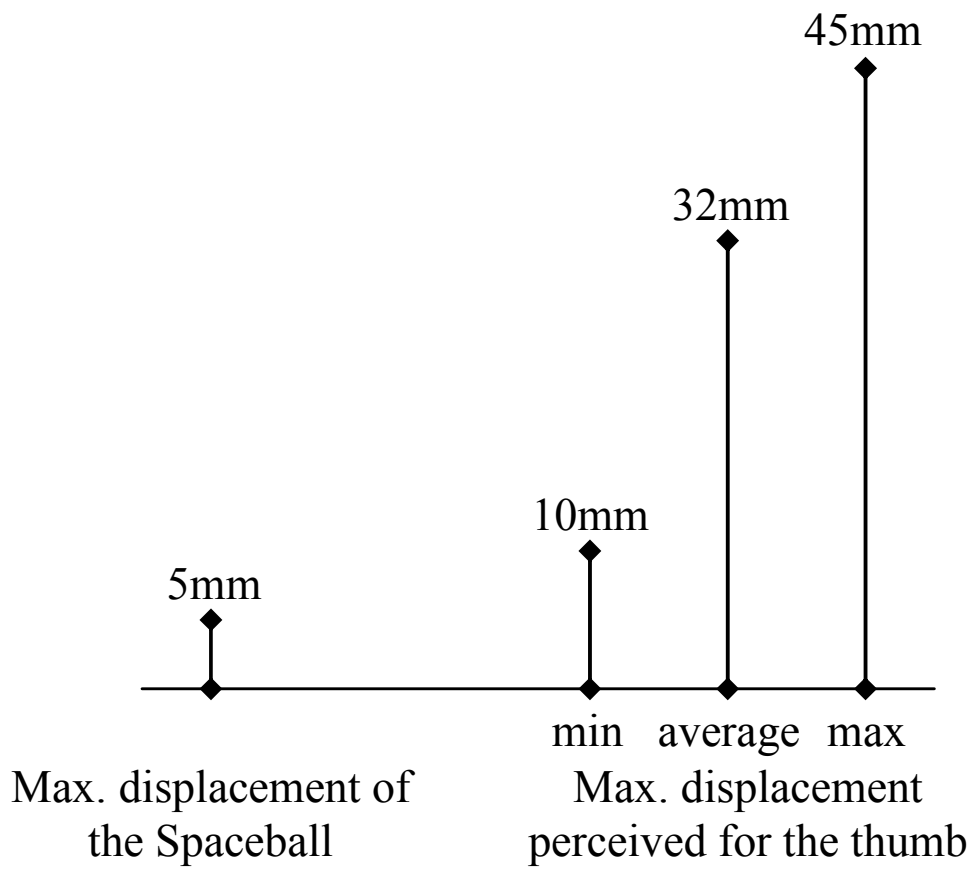**Figure 2: Pseudo-haptic simulation of the stiffness of a virtual piston using a Spaceball.**

Figure 3: Pseudo-haptic simulation of stiffness: Haptic illusion concerning the displacement of the user's thumb.
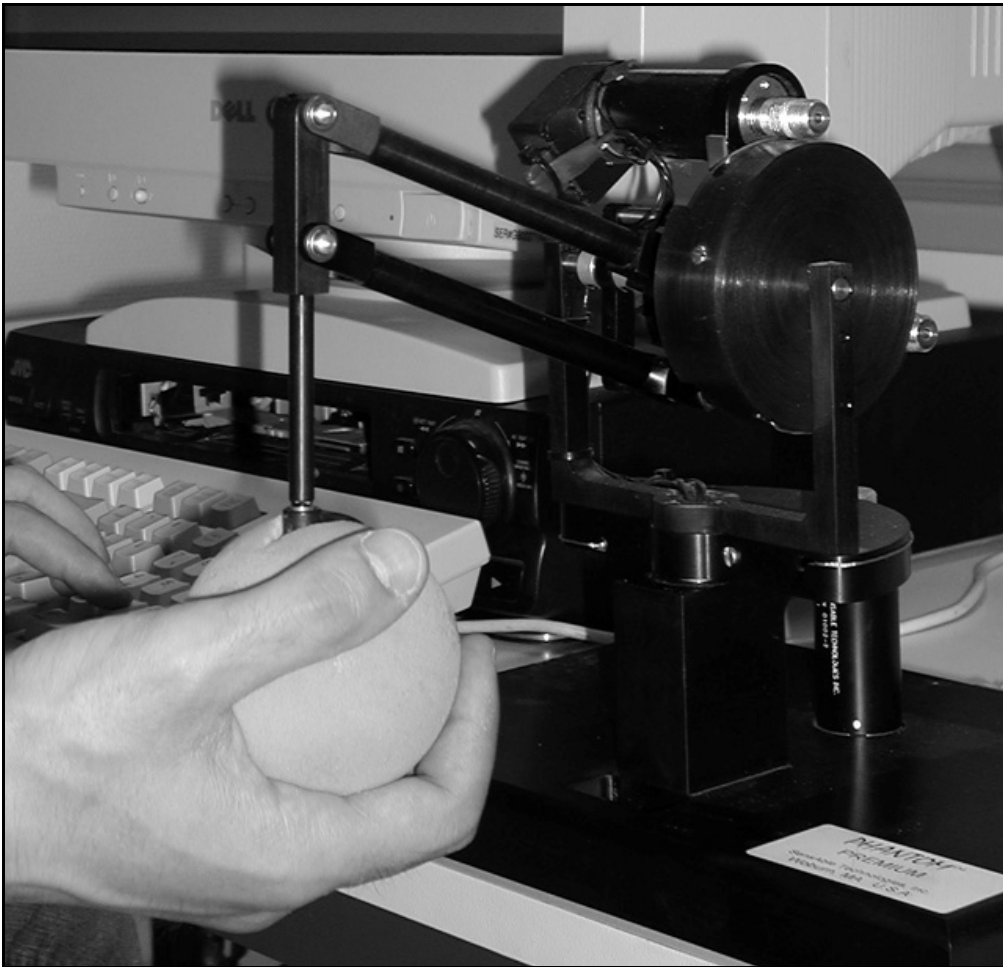
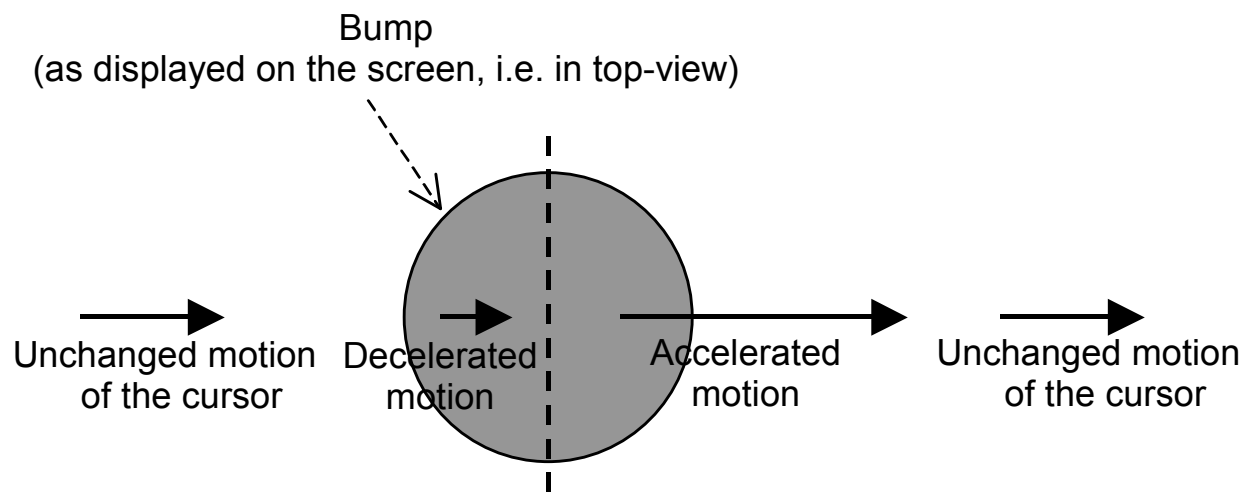**Figure 4: Experimental setup used by Dominjon et al. (Dominjon et al., 2005).**

Figure 5: A cursor moving over a pseudo-haptic bump. First, the cursor slows down (until it reaches the top of the bump) and then it speeds up.
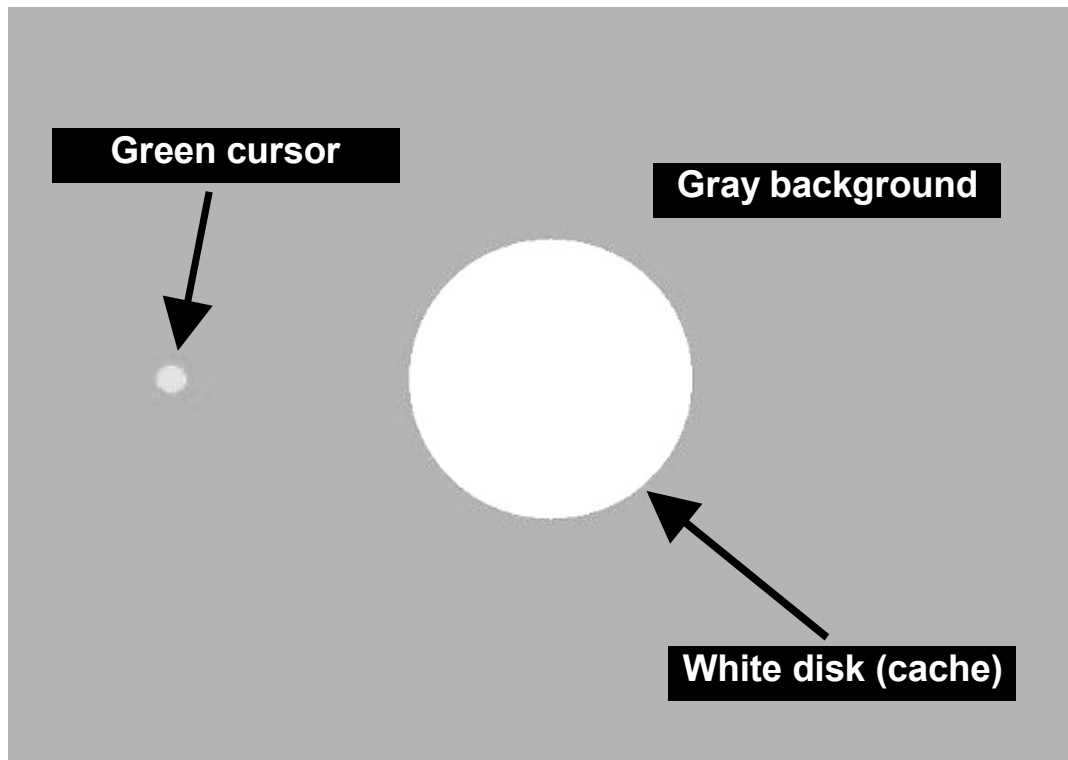
Figure 6: Experiment conducted in (Lécuyer et al., 2004a): subjects are asked to identify the surface (bump, hole or flat surface) hidden beneath the white cache.
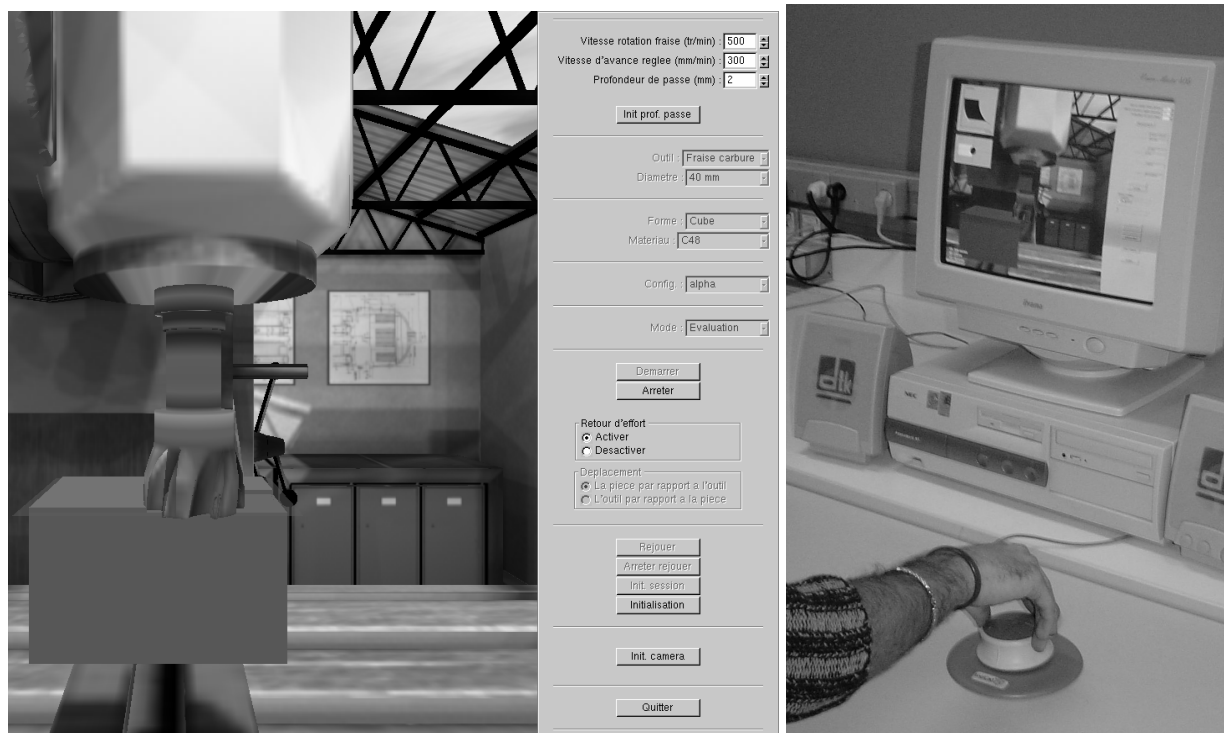
Figure 7: (a) Visual feedback of the Virtual Technical Trainer (VTT); (b) Pseudo-haptic feedback in VTT using a SpaceMouse.

Figure 8: Medical simulator for training in nerve stimulation

in loco-regional anesthesia (Bibin et al., 2008)